

Europa's Differentiated Internal Structure: Inferences from Four Galileo Encounters

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Abstract

*fly-by
orbital encounter
internal structure*

Radio Doppler data from four encounters of the **Galileo Orbiter** with the jovian moon **Europa** have been used to refine models of Europa's interior. Europa is most likely differentiated into a **metallic core** surrounded by a **rock mantle** and a **water ice-liquid outer shell**, but the data cannot eliminate the possibility of a uniform mixture of dense silicate and metal

beneath the water ice–liquid shell. The size of a metallic core is uncertain because of its unknown composition, but it could be as large as about 50% of Europa’s radius. The thickness of Europa’s outer shell of water ice–liquid must lie in the range of about 80 to 170 km.

The Galileo Orbiter mission has provided four Europa encounters (E4, E6, E11, E12; Table 1) at flyby distances close enough to reveal details of the satellite’s gravitational field [1]. Radio Doppler data were also generated from three more encounters (E13, E14, E15) at altitudes of 3558 km, 1648 km, and 2519 km, but they are not included. Here we remove all model ambiguities caused by previous inconsistent results [2], and we produce a new suite of interior models based on a factor of five improvement in Europa gravity.

On the basis of radio Doppler data generated by the Deep Space Network (DSN) at three 70 meter stations located at Goldstone California (DSS14), near Madrid Spain (DSS63), and near Canberra Australia (DSS43), and nonlinear weighted least squares [3], we have determined coefficients in the standard spherical harmonic expansion of the gravitational potential V [4] to the third degree. All other higher degree harmonics have been set to zero. Our results reveal a satellite in hydrostatic equilibrium at the ± 10 mGal level [5], hence we use the theory of equilibrium figures [6] to derive interior models consistent with the data. The data are not accurate enough [7] to determine the rigidity of materials within Europa by means of the method of periodic tidal deformations [8].

The flyby geometry for E4, E6, and E11 (Table 1), where along-track and cross-track components of the Doppler shift can be detected, is the most useful for determining gravitational perturbations. For E12 the spacecraft passed directly in front of Europa. Therefore, any gravitational perturbations for E12 are detected by the Europa-centered trajectory

bending only, while for the other three encounters the bending and the velocity perturbation along the orbital path contribute to the measured Doppler shift. The E11 data were considered less reliable than the E12 data because there was a ~ 14 minute gap in the data starting 4 minutes before closest approach, a significant fraction of the ~ 60 minute interval when the data were sensitive to the second degree gravitational field.

We combined the Doppler data from all four encounters (Table 1), along with ground-based astrometric data on the positions of the four Galilean satellites and optical navigational data from the Voyager and Galileo missions to Jupiter, to obtain models of Europa's interior structure. This combined solution includes adjustments to the satellite ephemerides, obtained by numerical integration of their equations of motion. The E4 data were included for purposes of improving the Europa ephemeris, but these data had a negligible effect on the determination of the gravitational coefficients (Table 1). We included the possibility of an atmospheric drag deceleration acting during E12 when the spacecraft altitude was less than one Europa radius [4]. We found that the E12 encounter data can be fit equally well with and without a drag model. Furthermore, a solution for the drag deceleration as a parameter in the model yields $0 \pm 3 \text{ mm s}^{-1}$ in integrated velocity change. The conclusion from the E12 data is that atmospheric drag is not detected, but for the adopted scale heights (240 km below 300 km altitude and 440 km above 300 km altitude), there is a 1σ upper limit on surface atmospheric density of $3 \times 10^{-11} \text{ kg m}^{-3}$. This limit is consistent with radio occultation results [10].

Because the given orientation of the satellite's axes predates the Voyager mission, we include all five second degree gravitational coefficients in the fit to the combined data. The two harmonics C_{21} and S_{21} of first order can be interpreted as corrections to the orientation

of the polar axis, while the coefficient S_{22} measures a rotation of the x and y axes about the polar axis z. The origin of coordinates is by definition at Europa's center of mass, hence the first degree harmonics C_{10} , C_{11} , and S_{11} are all zero and were not included in the fit. The seven third degree coefficients were included in the fit, but it is the second degree field that provides the important constraints on the interior structure, and those coefficients in units of 10^{-6} are, $J_2 = 435.5 \pm 8.2$, $C_{21} = -1.4 \pm 6.0$, $S_{21} = 14 \pm 12$, $C_{22} = 131.0 \pm 2.5$, $S_{22} = -11.9 \pm 2.9$ and $\mu = 0.993$.

The lack of a definite detection of C_{21} and S_{21} indicates that the orientation of Europa's polar axis needs no correction. If the x axis is aligned in the Europa-Jupiter direction, along the smallest principal moment of inertia A, then S_{22} should be zero. The negative value of S_{22} implies that the axis along A lies $2.60^\circ \pm 0.63^\circ$ west of the nominal x axis [11].

The major inconsistencies between the combined fit and the separate fits to each encounter (Table 1) are the J_2 and C_{22} values for E4. However, the apriori hydrostatic constraint assures that J_2 is 10/3 of C_{22} within the error limits, hence we are actually concerned with only one inconsistency, the parameter C_{22} . We have published plots of the Doppler residuals (observed Doppler minus model Doppler) for E4 and E6 using the fits of Table 1 [2]. A similar plot of E4 residuals from the combined fit is essentially identical to the published plot. We conclude that the two- σ bias in the C_{22} value from E4 (Table 1) is caused by systematic errors in the earlier fit to the E4 data, most likely low-frequency systematic errors in the non coherent Doppler data.

The value of C_{22} and Europa's average density [12] can be used to infer the moon's internal structure if we assume, as in our previous report [2], that the source of Europa's spherical harmonic degree two gravitational field is an equilibrium ellipsoidal distortion of

the satellite, a distortion produced by spin and tidal forces as Europa revolves around Jupiter in synchronous rotation with its orbital period. Under these conditions, C_{22} is related to the rotational parameter q_r by

$$C_{22} = \frac{3\alpha q_r}{4} \quad (1)$$

where q_r , the ratio of the centrifugal force to the gravitational force at Europa's equator [12], is a measure of the forcing for rotational flattening of the satellite, and α is a dimensionless response coefficient that depends on the distribution of density with depth inside the satellite ($\alpha = 0.5$ for constant density). For $C_{22} = 131.5 \pm 2.5$ in units of 10^{-6} [11], α is 0.3493 ± 0.0085 , where the errors in C_{22} and q_r contribute 1.9 and 1.5 % to the error in α [12]. From equilibrium theory and the value of α it follows that Europa's axial moment of inertia C , normalized to MR^2 , is $C/MR^2 = 0.346 \pm 0.005$. This value of C/MR^2 is less than 0.4, the value of C/MR^2 for a sphere of constant density, and it requires a concentration of mass toward the center of Europa [13].

The surface of Europa is covered by a layer of water ice, which may in turn overlie a liquid water ocean [14]. The gravity experiment cannot distinguish between liquid water and ice because their densities are similar, but it is clear that the interior of Europa must have a density greater than the mean value [2]. Silicates and iron compounds are the only sufficiently abundant materials with densities in this range, hence we explore three-layer models consisting of a water ice or liquid outer shell, a rock layer composed of silicates or a silicate-metal mixture, and an optional metallic core composed of Fe or an Fe-FeS eutectic mixture.

Because only mean density and C constrain the models, there are too many unknowns to

provide a unique inversion. We bound the parameter space with constraints on the densities of ice, including “dirty” ice–rock mixtures and some denser phases of ice which may exist near the bottom of the water ice layer, the densities of silicates and silicate–metal mixtures, the radius of the core, and the density of the core, which is either 8000 kg m^{-3} for the Fe, or 5150 kg m^{-3} for the Fe–FeS eutectic. We take a forward–modelling approach and solve Clairaut’s equation for α to determine the family of model parameters which satisfy our combined fit to all the observations. All the models have water ice–liquid shell thicknesses between about 100 and 200 km (Fig. 1).

Although two–layer models can be found that are consistent with the observations, we find these models implausible. Previously we argued for a metallic core based on magnetic field perturbations observed during the E4 flyby [15]. Subsequent observations have not confirmed an intrinsic European magnetic field, and are instead more consistent with plasma surrounding Europa and a time-varying induced magnetic field with a source near the surface [16]. Although an intrinsic magnetic dipole would have provided powerful evidence for a metallic core, other lines of evidence allow us to use the gravity data to confirm the presence of a European core.

Models of Europa’s interior that lack a metallic core are only consistent with the observed value of C_{22} if the interior is a mixture of rock and metal with a density greater than 3800 kg m^{-3} . This density implies that Europa’s interior is enriched in dense metallic phases relative to Io, which has a bulk density of 3529 kg m^{-3} [17]. If the metal is Fe, the enrichment is 12%, and the enrichment is even greater for lower density metallic phases such as magnetite. We suggest that such degrees of enrichment in dense phases are unlikely for a smaller body forming farther out in the proto–jovian nebula than Io. It is more likely

that this mixture would separate into a metallic core and rock mantle, because radiogenic heating in the silicates alone would raise Europa's interior to temperatures high enough for differentiation to occur[18], and tidal heating, though difficult to quantify, is potentially an important additional source of heating in the mantle. We conclude therefore that Europa has differentiated a metallic core, and we proceed to analyze 3-layer models which can satisfy the moment of inertia constraint without requiring Fe enrichment in Europa relative to Io.

The three-layer models of Europa have Fe and Fe-FeS cores of varying sizes depending on the density of the rock mantle; lower rock densities yield larger cores and thinner water ice-liquid outer shells (Fig. 1 and 2). The minimum water ice-liquid outer shell thickness in the three-layer models is about 80 km. Smaller outer shell thicknesses are possible only for mantle densities less than 3000 kg m^{-3} . Such small mantle densities are possible only if the mantle silicates are hydrated. In effect, the water in the outer shell is trading off with the water in hydrated mantle silicates. If the mantle density is sufficiently small ($< 3000 \text{ kg m}^{-3}$) there is enough density contrast between the mantle and metallic core to account for the relatively small moment of inertia of Europa. Otherwise, a thick water ice-liquid shell (100–200 km) is needed to provide the requisite density contrast between the exterior and deep interior of a differentiated Europa. Hydrated silicates break down and release their water at temperatures between 700 and 800°C at the pressures in Europa's interior [19], making it unlikely that a thick European mantle would have an average density less than 3000 kg m^{-3} . Furthermore, it is implausible that Europa would have differentiated a metallic core while retaining a hydrated silicate mantle.

References

- [1] The first encounter (E4) occurred on 19 December 1996, the second (E6) occurred on 20 February 1997, the third (E11) occurred on 6 November 1997, and the fourth (E12) occurred on 16 December 1997, where the encounter designation En refers to an encounter with Europa on the spacecraft's nth orbital revolution of Jupiter.
- [2] J. D. Anderson, E. L. Lau, W. L. Sjogren, G. Schubert, W. B. Moore, *Science* **276**, 1236 (1997).
- [3] See, for example, T. D. Moyer, *Tech. Rep. No. TR 32-1527* (Jet Propulsion Laboratory, Pasadena, CA, 1971); B. D. Tapley, in *Recent Advances in Dynamical Astronomy*, B. D. Tapley and V. Szebehely, Eds. (Reidel, Dordrecht, Netherlands, and Boston, MA, 1973), pp. 396-425; J. D. Anderson, in *Experimental Gravitation*, B. Bertotti, Ed. (Academic Press, New York, 1974), pp. 163-199.
- [4] W. M. Kaula, *Theory of Satellite Geodesy* (Blaisdell, Waltham, MA, 1966). The expression for V is

$$V(r, \phi, \lambda) = \frac{GM}{r} \left[1 + \sum_{n=2}^{\infty} \sum_{m=0}^n \left(\frac{R}{r} \right)^n (C_{nm} \cos m\lambda + S_{nm} \sin m\lambda) P_{nm}(\sin \phi) \right] \quad (2)$$

where M is the satellite's mass and G is the gravitational constant, $G = 6.67259 \pm 0.00085 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$, E. R. Cohen, B. N. Taylor, *Phys. Today* **50**, BG7 (1997). The spherical coordinates (r, ϕ, λ) are referred to the center of mass, with r the radial distance, ϕ the latitude and λ the longitude on the equator. Europa's reference radius R is $1,565 \pm 8 \text{ km}$, M. E. Davies, V. K. Abalakin, A. Brahic, M. Bursa, B. H. Chovitz, J. H. Lieske, P. K. Seidelmann, A. T. Sinclair, Y. S. Tjuffin, *Celes. Mech.* **53**, 377 (1992).

P_{nm} is the associated Legendre polynomial of degree n and order m , and C_{nm} and S_{nm} are the corresponding coefficients determined from the data.

- [5] A Gal (after Galileo) is commonly used in gravimetry. It is a unit of acceleration where $1 \text{ Gal} = 1 \text{ cm s}^{-2} = 10^{-2} \text{ m s}^{-2}$.
- [6] W. B. Hubbard, J. D. Anderson, *Icarus* **33**, 336 (1978); S. F. Dermott, *Icarus* **37**, 310 (1979); V. N. Zharkov, V. V. Leontjev, A. V. Kozenko, *Icarus* **61**, 92 (1985); S. Mueller, W. B. McKinnon, *Icarus* **76**, 437 (1988); G. Schubert, D. Limonadi, J. D. Anderson, J. K. Campbell, G. Giampieri, *Icarus* **111**, 433 (1994).
- [7] All estimated errors were taken directly from the covariance matrix associated with the data analysis. They were based on an assumed standard error of 2 mm s^{-1} for non-coherent Doppler and 1 mm s^{-1} for coherent Doppler at a sample interval of 60 s. For data sampled at 10 s near the closest approaches to Europa, the error was increased by $\sqrt{6}$. A weighting algorithm was applied that increased the assumed standard error on the data as the spacecraft elevation angle approached the DSN station's horizon.
- [8] An experiment to measure tidal variations on Titan during the Cassini orbital tour of the Saturnian system in 2004 to 2008 has been proposed by N. Rappaport, B. Bertotti, G. Giampieri, J. D. Anderson, *Icarus* **126**, 313 (1997). A similar experiment for Europa is feasible, but because of the smaller eccentricity of ~ 0.009 for Europa's orbit compared to an eccentricity of 0.029 for Titan, a future Europa orbiter mission would be required.
- [9] R. Woo, J. W. Armstrong, *J. Geophys. Res.* **84**, 7288 (1979).

- [10] A. J. Kliore, D. P. Hinson, F. M. Flasar, A. F. Nagy, T. E. Cravens, *Science* **277**, 355 (1997). The current best estimate of the surface number density is 10^{14} m^{-3} (D. P. Hinson, private communication), which for O_2 corresponds to a mass density of $5 \times 10^{-12} \text{ kg m}^{-3}$, about six times smaller than our upper limit.
- [11] For dynamical reasons, the principal axis must be directed on average toward Jupiter. The orientation of the axes in our software (ODP) was defined in 1980 based on Lieske's E2 ephemeris for the Galilean satellites, J. H. Lieske, *Astron. Astrophys.* **56**, 333 (1978). However, an adjustment of 1.54° in the location of zero longitude was made in 1982 so that Europa's 182° meridian passed through the crater Cilix in accordance with IAU convention [4]. Hence the definition of zero longitude in the ODP is based on Voyager imaging data, not on satellite dynamics. If Europa followed Lieske's E2 ephemeris, the 1980 x axis would point toward Jupiter and S_{22} would be zero. But with the 1982 definition, Jupiter would be 1.54° west of the x axis. Also, our current numerically integrated ephemeris does not agree with Lieske's E2 ephemeris, so we expect an additional offset. In the middle of November 1997, a date between E11 and E12, the mean position of Jupiter is at west longitude 1.17° according to our current ephemeris. The Europa gravity data yield an indirect determination for Jupiter's cartographic longitude of $2.60^\circ \pm 0.63^\circ$, 2.3σ from the actual location given by the ephemeris. We consider this not only a satisfactory agreement, but also an excellent check on the Doppler-determined gravity. The value of C_{22} in the system of rotated axes is $(C_{22}^2 + S_{22}^2)^{1/2}$, and S_{22} is zero by definition. The axis rotation increases C_{22} to 131.5 ± 2.5 in units of 10^{-6} and μ is reduced from 0.993 to 0.988.

- [12] Our best estimate for Europa's GM is $3202.72 \pm 0.05 \text{ km}^3 \text{ s}^{-2}$, R. A. Jacobson, *BAAS* in the press (1998). Using the best current values for G and R [4], we obtain a mass for Europa of $(4.79982 \pm 0.00062) \times 10^{22} \text{ kg}$ and a mean density of $2989 \pm 46 \text{ kg m}^{-3}$. The rotational parameter $q_r = \omega^2 R^3/GM$ is $(5.019 \pm 0.077) \times 10^{-4}$, where the angular velocity $\omega = 2\pi/P$ is determined from Europa's sidereal orbital period $P = 3.551 \text{ d}$, P. K. Seidelmann, *Explanatory Supplement to the Astronomical Almanac* (University Science Books, Mill Valley, CA, 1992). The errors in the density and q_r are dominated by the 8 km error in Europa's radius.
- [13] The gravity coefficient $C_{22}=131.5 \times 10^{-6}$ and the rotational parameter $q_r=5.019 \times 10^{-4}$ can also be used to compute the equilibrium shape of the Roche–Darwin ellipsoid [6]. In terms of the principal axes ($c < b < a$), where a is the equatorial radius, c is the polar radius, and b is the intermediate radius, the polar flattening is $(a-c)/c=2.056 \times 10^{-3}$. The distortion of the equatorial cross section can be expressed by the parameter $(b-c)/(a-c)$, which according to equilibrium theory, is exactly $1/4$. These shape parameters are consistent with the shape of Europa inferred from Galileo images, although the observed shape is subject to considerable uncertainty (P. Thomas, private communication). We use the axial moment of inertia C normalized to MR^2 as a constraint on the interior models. We ignore the small differences between the three principal moments ($\sim 0.1\%$).
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- 391**, 368 (1998); R. Sullivan et al., *Nature* **391**, 371 (1998).
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- [17] J. D. Anderson, W. L. Sjogren, G. Schubert, *Science* **272**, 709 (1996).
- [18] Because Europa and the Moon are similar in size and density, the expected temperature in an undifferentiated European mantle, produced by radiogenic heating, subsolidus convective heat transport, and temperature-dependent mantle viscosity, can be estimated from calculations carried out for the lunar interior. Lunar calculations are reported in G. Schubert, R. E. Young, P. Cassen, *Phil. Trans. Roy. Soc. London* **A285**, 523 (1977). The deep mantle temperature in these lunar models is between 1500 and 1600 K.
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Table caption

The location of the spacecraft's closest approach is given in the first three rows, where longitude is measured west of the Europa-Jupiter direction and altitude is referenced to a sphere of radius $R = 1565$ km [4]. The SEP angle is the elongation between the Sun and Jupiter. For SEP angles greater than 90° , the minimum amount of phase noise is introduced into the S-band (2.3 GHz) radio wave as it propagates through solar plasma [9]. The next three rows give the direction cosines of the Doppler line of sight for the Europa flyby trajectory at closest approach. The cross-track component is aligned with the Europa-spacecraft direction, the along-track component is aligned with the spacecraft's Europa-centered velocity vector, and the normal component is aligned with the spacecraft's Europa-centered orbital angular momentum vector. The quality of the available radio Doppler data depends on whether or not the data were coherent with hydrogen maser frequency standards at the DSN complexes. Coherency is achieved only when the spacecraft radio system is locked to a signal from a DSN station by means of its S-band transponder. Otherwise, the data are referenced to the spacecraft's crystal oscillator with its relatively poor frequency stability, unknown frequency bias, and unknown frequency drift. In fitting E4 and E6 data we included the bias and drift as parameters in the model. These two parameters are unnecessary for the coherent E11 and E12 data. Other factors, most importantly the continuity of the data and the location of data gaps with respect to the closest approach time, also affect the data quality. The last four rows give the results of the data analysis [7], with each flyby analyzed independently. In accordance with equilibrium theory [6], the coefficient J_2 (the negative of C_{20}) has been constrained a-priori to $10/3$ of C_{22} . The coefficient μ represents the correlation between J_2 and C_{22} from the post-fit covariance matrix. The last row of Table 1 represents an

estimate of the axial moment of inertia normalized to MR^2 from Radau–Darwin equilibrium theory [6]. It is not an independent parameter of the model, but is calculated from the inferred value of C_{22} . For a sphere of constant density, C/MR^2 is 0.4.

Table 1

TABLE 1. Europa Encounter Geometry and Gravity Results

	E4	E6	E11	E12
Latitude (deg)	-1.7	-17.0	25.7	-8.7
Longitude (deg)	36.8	324.7	140.6	225.0
Altitude (km)	697	591	2048	205
SEP (deg)	24.6	25.2	89.0	54.6
Direction Cosines for Line of Sight				
Cross Track	0.772	0.656	-0.744	-0.985
Along Track	0.634	0.729	0.569	0.068
Normal	-0.035	-0.194	0.350	-0.160
Coherent Doppler?	No	No	Yes	Yes
J_2 (10^{-6})	215 ± 102	438 ± 45	442 ± 28	438 ± 9
C_{22} (10^{-6})	65 ± 31	132 ± 13	133 ± 8	132 ± 2
μ	0.999	0.995	0.986	0.847
C/MR^2	0.264 ± 0.041	0.347 ± 0.014	0.349 ± 0.009	0.348 ± 0.002

Figure Captions

Fig. 1. Possible three-layer models of Europa consistent with its mean density and axial moment of inertia ($C/MR^2 = 0.346$). Two sets of models are considered, one having Fe cores with density 8000 kg m^{-3} and the other having Fe-FeS cores with density 5150 kg m^{-3} . Any point on one of the surfaces defines an interior structure with properties given by the coordinate axis values and the color of the surface. Ice density refers to the density of the outer spherical shell of the model which is predominantly water in either ice or liquid form with an admixture of some rock. The color of the surface gives the thickness of this outer shell according to the color bar. Rock density refers to the density of the mainly silicate intermediate shell which may also contain some metal. Possible Europa models are defined by the surfaces whose colors give the thickness of the water ice-liquid outer shell. Other model parameters, outer shell or ice density, intermediate shell or rock density, and core radius, are provided by the coordinate axes. two-layer Europa models are given by the intersection of the model surfaces with the core radius equal zero plane.

Fig. 2. Details of the intersection of the model surface of Fig. 1 with the horizontal outer shell density = 1050 kg m^{-3} plane. Europa three-layer models having an ice density (outer shell density) of 1050 kg m^{-3} are shown. The solid curve labelled 131.5 ($\times 10^{-6}$) defines models constrained by Europa's mean density and the indicated values of C_{22} used in constructing the model surfaces in Fig. 1. The curves designated 129 and 134 ($\times 10^{-6}$) delineate models with the $\pm 1 \sigma$ values of C_{22} . The curves labelled 50, 100, 150, etc., give the outer shell thickness in km.

Fig. 1. Possible three-layer models of Europa consistent with its mean density and axial moment of inertia ($C/MR^2 = 0.346$). Two sets of models are considered, one having Fe cores with density 8000 kg m^{-3} and the other having Fe-FeS cores with density 5150 kg m^{-3} . Any point on one of the surfaces defines an interior structure with properties given by the coordinate axis values and the color of the surface. Ice density refers to the density of the outer spherical shell of the model, which is predominantly water in either ice or liquid form with an admixture of some rock. The color of the surface gives the thickness of this outer shell according to the color bar. Rock density refers to the density of the mainly silicate intermediate shell, which may also contain some metal. Possible Europa models are defined by the surfaces whose colors give the thickness of the water ice-liquid outer shell. Other model parameters (outer shell or ice density, intermediate shell or rock density, and core radius) are provided by the coordinate axes. Two-layer Europa models are given by the intersection of the model surfaces with the core radius = 0 plane.

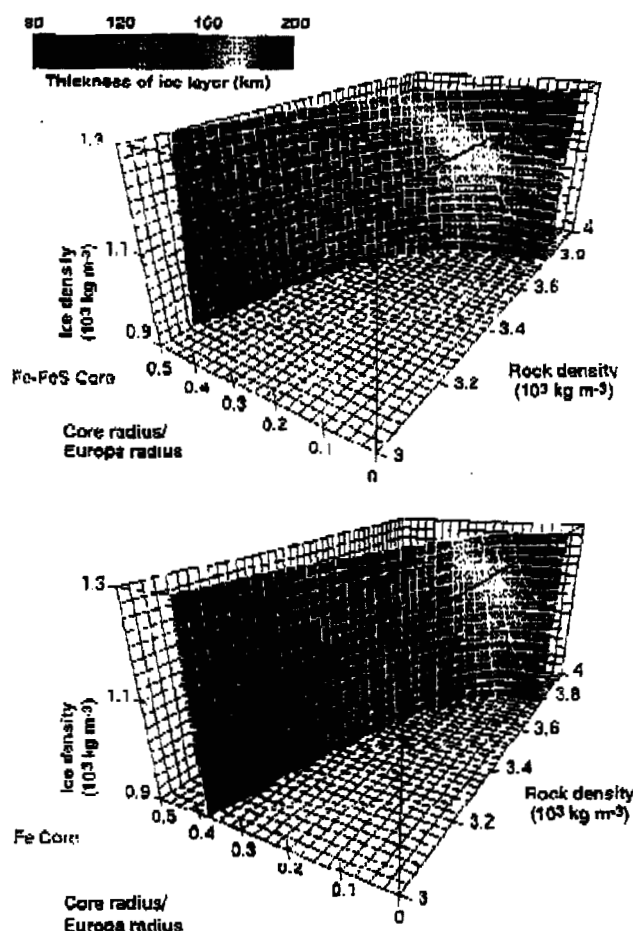
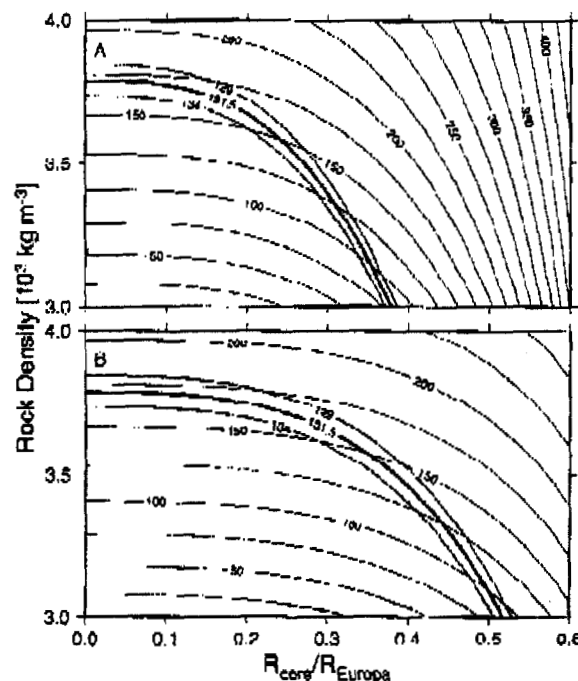


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300 km altitude), there is a 1σ upper limit on surface atmospheric density of $3 \times 10^{-11} \text{ kg m}^{-3}$. This limit is consistent with radio occultation results (9).

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Orig. Op.	OPERATOR:	Session	PROOF:	PF's:	AA's:	COMMENTS:	ARTNO:
1st Disk, 2nd	daviess	4					Fig. 1 - 4/C